BULLETIN

OF

The Terrestrial Electric Observatory

OF

FERNANDO SANFORD
Palo Alto, California

VOLUME II

Summary of Observations on Earth Potential, Air Potential Gradients, and Earth-Currents, September, 1923–December, 1924

Palo Alto, California
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SUMMARY OF OBSERVATIONS ON EARTH POTENTIAL, AIR POTENTIAL GRADIENTS, AND EARTH-CURRENTS, SEPTEMBER, 1923–DECEMBER, 1924

On Some Possible Causes of a Diurnal Variation in the Readings of a Quadrant Electrometer

In Volume I of the bulletin of this observatory were published the results of a long series of measurements of what was believed to be a diurnal variation of the electric potential of the earth at this station, and a discussion in which the proposed explanation of this variation was found in an electrostatic induction by a negatively electrified sun and a negatively electrified moon upon the earth. The method by which this diurnal variation was detected was described, but owing to lack of space the possible causes of variation in a quadrant electrometer used as was the one in the investigation were not fully discussed. Since that time there have been a number of suggestions of other possible ways than the one suggested of accounting for the observed results, so that it seems proper to begin this report with a discussion of these possibilities.

The arrangement of the electrometer and its connections was shown in Figure 2 of Volume I, and for the purpose of this discussion this figure is reproduced here as Figure 1. In this figure, E represents a quadrant electrometer of which *a* and *b* are the quadrant pairs. The electrometer stands on a wooden pier, which is not shown in the figure. One quadrant pair, marked *a,* is connected by a copper wire to the metal case of the instrument, and through it to the wire cage surrounding the whole apparatus and to the water system of Palo Alto. The other pair of quadrants, *b,* is connected by an enameled copper wire to an insulated conductor, C, which consists of a coil of copper wire which is immersed in a dilute copper sulphate solution in a Dewar flask. The flask is contained in a metal case, and this case is placed in a heavy porcelain jar, from which it is insulated by paraffin blocks. The jar has a porcelain cover through which the wire from *b* passes, and the wire is insulated from both the jar and the Dewar flask by paraffin plugs. For most of the distance between the electrometer and C the connecting wire passes through glass tubes, but these tubes are open at both ends.

The electrometer needle is permanently attached to one pole of a battery of dry cells, the other pole of which is connected to a surrounding cage of window screen wire, to the outer cage and to the earth, as shown in the figure. The apparatus is set up inside a room four feet square and eight feet high, the walls, floor and ceiling of which are lined with wire netting, which is connected by a soldered wire to the city water system.

The lamp and recording drum upon which the electrometer deviations are photographed are outside this room.

With this arrangement, the electrometer and the insulated conductor remain continuously in a closed, earthed, hollow conductor, and one pair of quadrants remains in electrical contact with the inside of this hollow conductor and with the earth. The whole apparatus is effectually screened

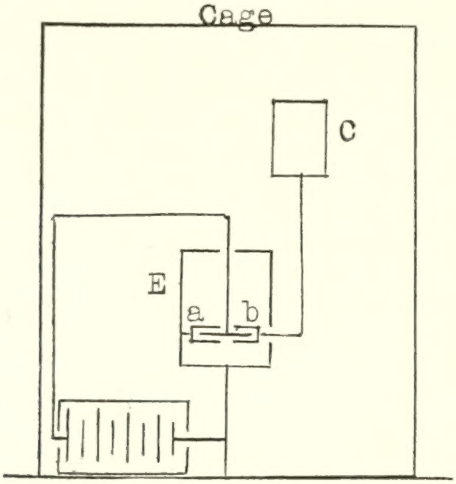

FIGURE 1.

Diagram of electrometer connections for measuring variations of earth potential. E indicates the electrometer, of which *a* and *b* are the quadrant pairs. The needle is charged from the battery indicated below. C is an insulated conductor connected to one pair of quadrants, the other pair being earthed.

from the induction of outside charges, but not from free ions in the air. The insulated conductor to which one pair of quadrants is attached was, in the beginning, at the same potential as the earthed quadrants. With this arrangement of apparatus a diurnal variation of potential difference between the two pairs of quadrants has been almost continuously recorded for more than four years, during which time there has not been a single day without a variation.

There are several possible ways of building up a potential difference between the two pairs of quadrants of an electrometer when one pair is insulated and the other pair is grounded. In the first place, there will be an induced charge upon both pairs of quadrants due to the induction of the charged needle. In the case of the earthed quadrants this (induced) charge will be opposite in sign to the charge upon the needle, while charges of both signs will be induced upon the insulated quadrants. These charges will be separated as far as possible, and the charge of opposite sign to the

needle charge will be greater, the greater the distance and the greater the electrical capacity of the insulated conductor which is connected to this pair of quadrants.

Since the induced charges upon the two pairs of quadrants are not of the same magnitude and are not distributed in the same manner, there will, in general, be a change in the null reading of the uncharged electrometer when the needle is charged. If the two quadrant pairs be now connected, the needle may return approximately to its uncharged condition; but as soon as the quadrants are separated the needle will begin to drift.

This drift is explained by the leakage of the needle charge through the air to the insulated quadrants.* The air seems always to contain some free ions, and ions of the same sign as the needle charge are driven to both pairs of quadrants by the electric field of the needle. While the charges driven in this way to the grounded quadrants may escape to earth, the insulated quadrants will gradually become charged in the same sense as the needle.

So long as this charge is being built up on the insulated quadrants the needle will continue to drift. This may continue for several hours, or even for days, depending upon the capacity and the insulation of the conductor attached to the quadrants. Finally, a stage will be reached when the leakage, through the air and otherwise, from the insulated quadrants and the connected conductor will just balance the leakage to them from the charged needle. When this condition has been reached, the electrometer needle remains in a state of approximate equilibrium, and the instrument is now ready for use in making measurements.

But it is well known that the number of free ions in the air is not a constant quantity. While this number varies from place to place, it also has a diurnal and a seasonal variation at any given place.† Since a change in the rate of leakage of charge to and from the insulated quadrants will not, in general, be the same, there may be a diurnal variation in the electrometer deflection due to this cause. This variation may be in either direction, depending on which leakage current changes most with a change in the conductivity of the air.

In most places the conductivity of the air reaches its highest maximum about four o'clock in the morning, with a lower maximum about four in the afternoon. The electrometer deflections due to a change in atmospheric conductivity should accordingly show a maximum or minimum at these times.

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* See J. G. Brown, *Phys. Rev.*, 23, 665 (May, 1924).

† Mache u. v. Schweidler, *Die Atmosphärische Elektrizität*, S. 70.
Kähler, *Luftelektricität*, S. 66.
Dorno, *Licht und Luft des Hochgebirges;* Tabellen.

That the variations which have been recorded by my apparatus are not due to variations in atmospheric conductivity is indicated by the fact that the maxima and minima of electrometer deflection do not agree in time with the maxima and minima of atmospheric conductivity as recorded at other stations. Thus, in Figure 2 Curve A shows the mean diurnal variation of atmospheric conductivity at the Potsdam Observatory for the year 1910–11, as shown on page 66 of Kähler's *Luftelektricität*, and Curve B shows the mean diurnal variation in potential difference between the insulated and grounded quadrants of my electrometer for the three years, August, 1920–July, 1923. The principal maximum of Curve A does not appear at all in Curve B.

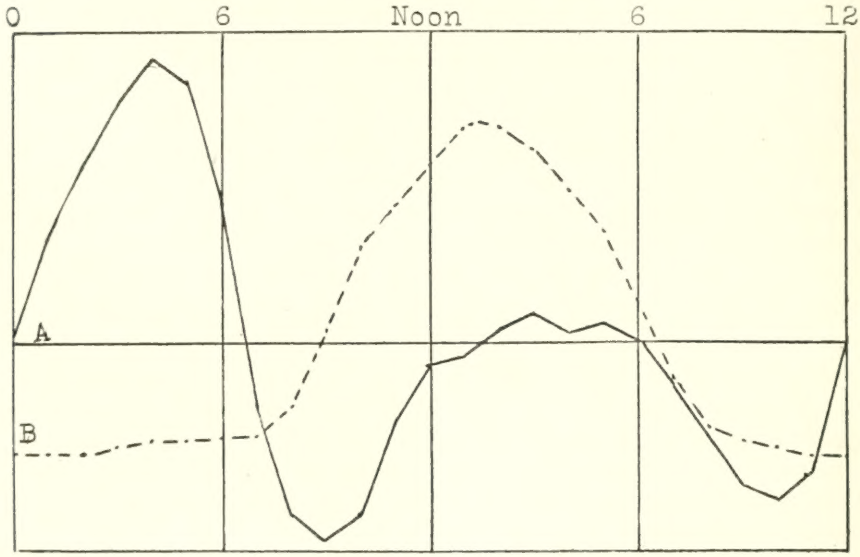

FIGURE 2.

Comparison of diurnal variation of atmospheric conductivity at Potsdam with diurnal variation of earth potential at Palo Alto.

Curve A indicates atmospheric conductivity and Curve B, variation of earth potential.

Fortunately, there is a possibility of deciding conclusively that the electrometer deflections recorded by my apparatus are not due to leakage currents from the charged needle. In the case of deflections due to the ionization of the air the direction of the deflection should be, and is, independent of the sign of the charge upon the electrometer needle. Thus, whether the needle be positively or negatively charged, the leakage charge which gathers on the insulated quadrants will be of the same sign as the

charge upon the needle, and the needle will be deflected away from the insulated quadrants. Consequently, the direction of deflection produced by a change in the conductivity of the air will be independent of the sign of the needle charge.

On the other hand, if the charge upon the earthed quadrants is changed by a flow of electricity to or from the earth, the direction of the needle deflection will depend upon the sign of its charge. Reversing the sign of the charge upon the needle, other conditions remaining the same, will reverse the direction of the diurnal variation if it is due to a change of charge on the earthed quadrants, but will not affect its direction if it is due to leakage currents from the needle. In the present investigation the sign of the needle charge has been reversed a number of times without any other change in the arrangement of the apparatus, and the direction of the diurnal variation of the electrometer deflection has invariably reversed with it.

It has been suggested that the recorded variation might be due to a diurnal change in the e.m.f. of the battery which charges the needle. This objection has been answered in two different ways. The battery which has been used to charge the needle during the past year had its e.m.f. measured at room temperature and after it had been immersed for an hour in a bath of melted paraffin, and the total change was only about three per cent, while the diurnal change in needle deflection has often amounted to several hundred per cent. Also, in Volume I of this bulletin mention was made of the fact that the diurnal electrometer variation was greater when the needle was suspended by a quartz fiber and no battery was attached than when it was continuously connected with the battery by a metal suspension. This conclusively eliminates the possibility of the observed variations being caused by a diurnal change in the e.m.f. of the battery by which the needle is charged.

There still remains the possibility of a periodic variation due to temperature changes, and the precautions which were taken to eliminate this possibility were described in Volume I. Thus, the single potential difference between a copper wire and a dilute copper sulphate solution is generally taken as 0.5 to 0.6 volt. The temperature coefficient of this potential difference is given by Arrhenius* as $dV/dT = .000766V$. Letting $V = 0.6$ volts, a change of temperature of one degree C inside the Dewar flask would give a potential variation of less than 0.46 mv. The highest electrometer sensitivity which I have used in the investigation would give a deflection of about 11 cms. on my record sheet for one volt potential difference between the electrometer quadrants. Under these conditions, a change of temperature of 20 degrees C inside the Dewar flask would be

* Arrhenius, *Elektrochemie,* S. 226.

required to give a deflection of 1 mm. on my record sheet. The mean daily range of variation on the record sheet for the year September, 1922–August, 1923, was 12.5 mm., which would require a mean daily temperature variation of 250° inside the Dewar flask. Maximum and minimum thermometers were kept in the room with the apparatus during that year, and the greatest variation in room temperature observed in one day was 32 degrees, F. The temperature change inside the Dewar flask must have been very small, and any variation in potential difference between the electrometer quadrants due to this cause was certainly inappreciable.

The above considerations seem to make it certain that the daily variation in potential difference between the two pairs of electrometer quadrants which has been recorded in this investigation cannot be explained by any known cause of variation of charge on the insulated quadrants and the attached conductor, or by any variation of charge on the electrometer needle due to a change in the e.m.f. of the charging battery. The only possible explanation which seems to be left is that the charge on the earthed electrometer quadrants undergoes a diurnal periodical change. In general, the earthed quadrants are more electropositive in the daytime than at night, which indicates that the day side of the earth is, on the whole, more electropositive than the night side.

The curves given on page 15 of Volume I show that the distribution of the electric charge of the earth undergoes not only a daily variation, but a seasonal variation as well. Such variations can be explained only by some physical relation between the sun and the earth. Since there is no known method of maintaining a separation of positive and negative charges upon a conductor except by the electrostatic induction of an outside charge, it seems necessary to assume the existence of a negative charge of great magnitude upon the sun.

Results of Earth Potential Variation for the Sixteen Months, September, 1923–December, 1924

In Volume I of this bulletin are given tables showing the monthly mean diurnal variations of earth potential at this observatory from July, 1920–August, 1923. In the following table are given the same data for the months September, 1923–December, 1924.

TABLE I.

Monthly Mean Diurnal Variation of Earth Potential, September, 1923–December, 1924.

A. M.	1	2	3	4	5	6	7	8	9	10	11	Noon
Sept.	−4.0	−4.2	−4.0	−4.3	−4.2	−4.5	−3.5	−3.3	−2.0	+4.2	+8.5	+9.5
Oct.	−1.0	−2.0	−2.0	−2.0	−2.0	−2.0	−1.0	−2.0	−2.0	0	+3.0	+5.0
Nov.	−1.1	−1.4	−1.4	−1.1	−1.0	−0.7	0	+0.1	0	+0.1	+3.8	+6.9
Dec.	−1.6	−1.4	−1.3	−1.2	−1.3	−1.2	−0.1	−0.8	−0.5	+2.1	+5.8	+8.1
Jan.	−2.2	−2.0	−1.7	−1.5	−1.2	−1.0	−0.7	−0.5	−0.1	+2.7	+5.3	+9.0
Feb.	−0.8	−0.5	−0.3	0	+0.3	+0.3	+0.4	+0.5	+0.7	+5.0	+6.0	+4.6
March.	−2.3	−2.1	−1.9	−1.7	−1.5	−1.2	−1.2	+1.1	+4.3	+9.5	+9.3	+8.3
April.	−1.1	−0.5	−0.4	−0.3	−0.1	+0.1	−1.6	+0.6	+2.8	+4.0	+3.2	+2.8
May.	−1.0	−1.2	−1.0	−1.0	−0.8	−0.8	−3.0	−1.2	+1.9	+5.1	+4.2	+5.9
June.	+7.3	+8.0	+8.3	+8.8	+8.7	+7.6	+6.3	+7.4	+6.3	+3.0	−2.1	−6.4
July.	+2.7	+3.2	+3.0	+3.2	+3.1	+1.4	+0.9	+2.4	+3.3	+4.7	+2.2	+0.4
Aug.	+2.4	+2.3	+2.1	+2.0	+1.7	+1.3	−0.1	+0.3	+1.3	+2.3	+2.4	+1.2
Sept.	+0.6	+0.4	+1.5	+0.9	+1.4	+1.9	+0.8	+1.5	+2.9	+5.4	+3.4	+2.1
Oct.	−0.5	−0.2	+0.5	−0.1	+0.4	+1.1	+0.3	+0.5	+2.2	+3.7	+4.1	+3.5
Nov.	−0.3	+0.8	+1.6	+1.9	+2.1	+2.5	+2.9	+2.5	+2.9	+6.8	+7.8	+5.4
Dec.	−0.4	−0.2	−1.0	−1.1	−1.0	−0.9	−0.3	−0.3	+0.2	+3.1	+3.2	+3.4
P. M.	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**
Sept.	+8.2	+5.2	+4.2	+3.2	+3.0	+1.6	0	−0.6	−1.2	−2.0	−3.0	−3.3
Oct.	+5.0	+4.0	+3.0	+3.0	+2.0	+1.0	0	0	0	0	0	−1.0
Nov.	+4.2	+1.3	0	+1.0	+0.5	−1.7	−1.9	−1.4	−1.4	−1.4	−1.4	−1.4
Dec.	+5.1	+2.4	+0.4	+0.1	−0.5	−1.4	−2.0	−1.7	−1.6	−1.5	−1.6	−1.4
Jan.	+7.5	+4.6	+2.2	+0.5	−0.1	−1.6	−2.4	−2.5	−2.4	−2.4	−2.3	−2.3
Feb.	+1.9	−0.5	−1.3	−1.8	−2.2	−2.4	−2.5	−2.3	−1.8	−1.7	−1.2	−1.0
March.	+6.0	+3.8	+1.8	+0.5	−1.2	−3.4	−5.2	−6.0	−5.5	−4.5	−3.6	−2.3
April.	+1.9	+1.2	+0.6	−0.3	−1.4	−2.2	−2.5	−2.2	−1.4	−0.5	+0.2	−0.3
May.	+5.5	+4.9	+3.7	+3.8	+1.0	−0.8	−0.4	−5.6	−5.8	−5.3	−3.4	−1.3
June.	−8.1	−9.9	−10.0	−9.5	−7.9	−9.4	−9.2	−5.7	−2.4	0	+3.5	+6.2
July.	−1.2	−2.4	−2.1	−2.7	−3.7	−4.7	−5.4	−5.4	−3.8	−2.3	−0.1	+1.8
Aug.	+0.5	−0.3	−0.8	−1.9	−2.9	−4.0	−4.0	−3.9	−2.6	−1.2	+0.8	+2.1
Sept.	+1.7	+0.7	−0.1	−0.4	−0.7	−3.1	−4.8	−5.9	−4.3	−3.5	−1.7	+0.6
Oct.	+1.8	+0.5	+0.1	−1.3	−2.3	−4.2	−3.7	−3.3	−2.7	−2.2	−1.5	−1.0
Nov.	+1.2	−2.6	−4.1	−4.2	−5.3	−6.4	−5.7	−4.1	−3.3	−2.3	−1.7	−0.3
Dec.	+1.8	+1.3	−0.3	−0.6	−1.0	−2.1	−1.6	−1.0	−0.8	−1.5	−0.4	−0.3

In Volume I the earth potential variation is expressed in terms of millivolts which introduced between the electrometer case with its attached quadrants and the earth would give the observed deflection. During the first half of the period covered by this report the electrometer case was not insulated from the pier upon which it stood, and it was impossible to introduce a cell between it and the earth. For this reason the deviations recorded in Table I are given in millimeters upon the recording sheet. The charge upon the electrometer needle was varied several times during the year, so the records of the different months are not strictly comparable in magnitude and should not be used for determining the seasonal variation.

An inspection of Table I will show that the months of June, July, August, and September, 1924, show a different type of variation from the other months. This change in type occurred quite abruptly about the 20th of May and changed back gradually to the former type during the late part of September and the early part of October. On account of my absence during the second half of October, no records were kept for that period, but the records for the first eleven days of that month give a curve more like those of the latter than of the former months.

A somewhat similar variation in the curves for the summer months is shown in the records of previous years, though the distinction between the two types has not appeared so marked.

The two curves are shown in Figure 3, where Curve A represents the diurnal variation of earth potential for twelve months of the period covered by this report, and Curve B represents the mean diurnal variation for the months June, July, August, and September, 1924. Curve A is based upon the records of 301 days, and Curve B upon the records of 110 days.

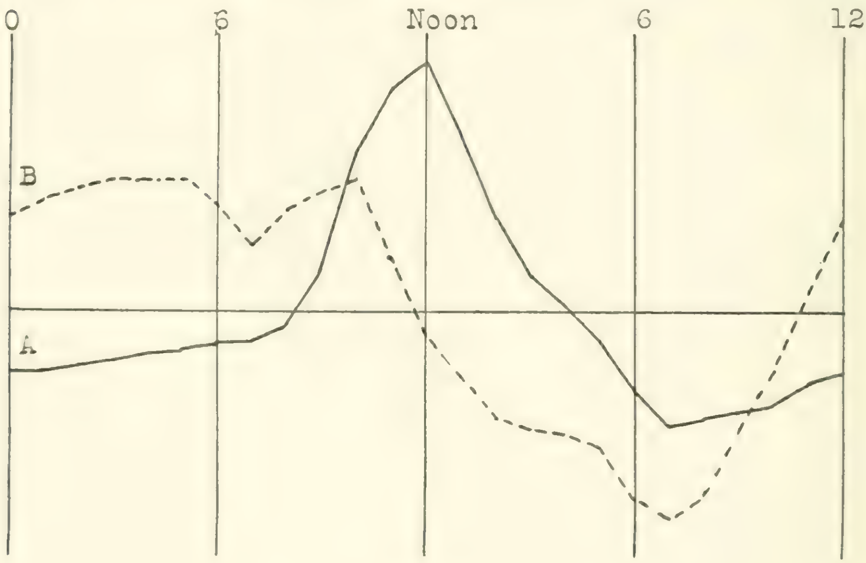

FIGURE 3.

Curve A represents the mean diurnal variation of earth potential for 12 months between September, 1923, and December, 1924, excluding the months June, July, August, and September, 1924.

Curve B represents the mean diurnal variation of earth potential for the months June–September, 1924.

Diurnal Variation in Atmospheric Potential Gradient

It was stated in Volume I that an attempt would be made during the following year to compare the diurnal variation in atmospheric potential gradient with that of the earth potential, and this comparison is perhaps the most important contribution of the present volume.

Since most previous measurements of atmospheric potential have been made between the earth and a point in the air, they must necessarily have included both the variations of the air potential and those of the earth potential. To eliminate the changes in earth potential from these records, all the air potential measurements here recorded have been made between two points in the air, one of which is higher than the other.

A mast extending about four meters above the building in which the measuring apparatus is placed has two arms, each one meter long, extending at right angles to the mast. One of these is at the top of the mast, and the other has been, for most of the measurements here reported, two meters below it. Recently this distance has been increased to three meters. Insulated wires run to the ends of the arms, where they end in a brush of fine wire and a small disc of the radioactive material which is used on luminous watch dials. These wires are carefully insulated for their entire length, and are attached at their lower ends to the quadrant pairs of a Dolezalek electrometer, the needle of which is kept charged by a battery of dry cells, the other terminal of which is earthed. The electrometer stands on a wooden pier, and is shielded from external induction by a wire cage. Previous to February 12, 1924, the electrometer stood on a pier about eight feet distant from the electrometer which is used to measure the earth potential variation. For the rest of the time it has stood on the same pier with the earth potential electrometer, and for several months the needles of the two electrometers were charged from the same battery.

The different positions of the electrometer and the different sources from which the needle has been charged have made no appreciable difference in the character of the daily variation. However, it was noticed that a sudden change in the charges on the air potential quadrants would induce an instantaneous change in the charge upon the needle and this would, in turn, cause a momentary deflection of the needle of the earth potential electrometer when the two needles were connected together and to the same battery. For this reason the two electrometers have since been charged from separate batteries.

The potential difference between the two points in the air has always been small, usually of about the order of one volt. The building upon which the mast is placed is surrounded at distances of from twenty to fifty feet by trees, several of which are much higher than the mast, and the surfaces of equal potential in the air are accordingly convex to the earth

and widely separated in the region where the measurements are being made. This is an advantage if the measurements are to be made by a sensitive electrometer, since it permits a much wider separation of the two air terminals than would be possible over a plane region. On the other hand, it does not permit any estimate of the actual magnitude of the potential gradient over the surrounding country. The values here given are accordingly only relative, and are expressed in terms of electrometer deflections instead of in volts per meter.

The mean monthly values of the diurnal variation in potential difference between the two points in the air for fifteen months are given in Table II. The records for April, 1924, are omitted from the table because

TABLE II.

Monthly Mean Diurnal Variation of Atmospheric Potential Gradient for the Period September, 1923–December, 1924.

A. M.	1	2	3	4	5	6	7	8	9	10	11	Noon
Sept	+ 2.9	+ 4.1	+ 5.4	+ 5.9	+ 7.4	+ 8.4	+ 8.2	+ 3.3	+ 3.4	+ 4.1	+ 0.9	− 4.3
Oct...	− 3.0	− 2.0	− 1.0	+ 0.8	+ 1.4	+ 1.7	+ 4.5	+ 8.6	+ 8.4	+ 4.8	+ 3.9	+ 0.6
Nov...........	+ 12.0	+ 10.5	+ 10.0	+ 10.0	+ 8.1	+ 7.5	+ 7.3	+ 12.7	+ 7.6	− 31.4	− 16.6	− 28.8
Dec..	+ 5.7	+ 5.2	+ 4.2	+ 5.4	+ 5.1	+ 6.1	+ 6.1	+ 7.0	+ 9.0	− 15.5	− 35.0	− 28.0
Jan.....	+ 13.0	+ 15.0	+ 15.0	+ 17.0	+ 17.0	+ 18.0	+ 17.0	+ 14.0	+ 4.0	− 19.0	− 39.0	− 35.0
Feb...	− 2.0	− 2.4	− 2.4	− 2.4	− 4.1	− 3.7	− 3.4	− 3.6	− 3.7	− 5.3	− 6.0	− 2.0
March	+ 1.9	+ 1.0	− 0.5	− 1.0	− 1.3	− 1.1	− 0.8	− 1.4	− 3.0	− 7.9	− 6.7	− 4.2
May.....	− 4.3	− 6.1	− 5.4	− 5.8	− 5.0	− 6.5	− 5.1	− 5.0	− 2.2	− 1.7	+ 1.6	+ 6.2
June.....	− 5.5	− 3.8	− 6.0	− 7.1	− 7.2	− 11.1	− 4.2	− 13.1	− 21.2	− 8.1	+ 3.3	+ 6.0
July	− 15.0	− 14.6	− 14.9	− 13.5	− 12.5	− 11.5	− 8.0	− 1.3	− 3.5	+ 2.6	+ 7.5	+ 3.5
Aug.	− 10.7	− 10.1	− 8.1	− 7.4	− 6.4	− 4.4	+ 14.4	+ 15.0	+ 12.3	+ 8.7	+ 2.6	− 1.5
Sept..	− 1.8	− 2.7	− 3.9	− 3.4	− 4.3	− 4.5	+ 0.8	− 2.3	+ 4.0	+ 3.0	+ 3.5	− 1.6
Oct.	+ 1.1	− 1.2	+ 0.5	+ 0.7	− 2.7	− 3.1	− 1.0	− 1.4	− 2.1	+ 0.1	− 2.3	− 7.0
Nov..	+ 7.4	+ 9.1	+ 8.0	+ 10.1	− 11.1	− 0.9	+ 3.1	+ 6.0	+ 4.1	− 21.1	− 5.3	− 2.4
Dec.	+ 1.1	+ 0.7	+ 0.4	+ 0.3	+ 0.2	0	0	+ 0.4	0	− 1.3	− 1.4	− 2.0
P. M.	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**
Sept	− 8.1	− 9.3	− 10.1	− 8.5	− 7.4	− 6.6	− 5.5	− 4.6	− 1.3	+ 1.5	+ 2.2	+ 1.9
Oct.	− 0.8	− 1.7	− 3.4	− 2.5	+ 1.0	+ 2.8	+ 3.8	− 0.3	+ 0.2	− 0.2	− 0.2	− 1.7
Nov.	− 1.8	− 11.4	− 4.6	− 5.7	+ 2.2	+ 3.5	+ 3.0	+ 6.0	+ 10.0	+ 10.8	+ 10.0	+ 11.6
Dec......	− 19.5	− 12.0	− 7.9	− 5.0	0	+ 5.3	+ 9.0	+ 10.0	+ 11.2	+ 11.4	+ 6.5	+ 4.5
Jan.......	− 27.0	− 19.0	− 15.0	− 9.0	− 9.0	− 2.0	+ 3.0	+ 5.0	+ 8.0	+ 9.0	+ 11.0	+ 11.0
Feb..	+ 1.7	+ 5.0	+ 5.0	+ 5.0	+ 5.0	+ 5.3	+ 6.1	+ 4.3	+ 2.7	+ 7.0	− 0.7	− 0.7
March	− 1.2	+ 0.7	+ 1.2	+ 1.6	+ 2.2	+ 3.0	+ 3.6	+ 3.7	+ 3.2	+ 3.2	+ 1.0	+ 1.5
May	+ 6.6	+ 7.7	+ 5.4	+ 6.4	+ 7.5	+ 11.7	+ 7.3	+ 6.4	− 2.7	− 7.1	− 8.6	− 6.3
June	+ 7.7	+ 10.4	+ 10.7	+ 11.2	+ 10.7	+ 16.4	+ 17.1	+ 7.4	− 3.0	− 2.1	− 7.6	− 6.7
July	+ 6.8	+ 1.7	+ 4.5	+ 6.0	+ 18.7	+ 30.7	+ 34.5	+ 19.4	− 2.2	− 11.2	− 14.7	− 13.6
Aug.	− 7.3	− 8.4	− 8.5	− 5.2	+ 0.7	+ 10.9	+ 18.0	+ 9.1	+ 2.9	− 0.3	− 3.9	− 8.7
Sept.	− 4.8	− 5.3	− 2.9	− 3.6	+ 1.3	+ 8.9	+ 5.4	+ 6.8	− 5.6	+ 4.8	+ 0.5	− 2.6
Oct.......	− 9.8	− 7.0	− 5.5	+ 0.1	+ 4.1	+ 7.0	+ 13.2	+ 8.8	+ 4.3	+ 2.2	+ 1.2	+ 2.0
Nov..	− 9.0	− 10.3	− 9.4	− 9.9	− 6.1	− 3.0	− 2.6	− 0.7	+ 7.1	+ 4.1	+ 2.7	+ 10.4
Dec......	− 2.1	− 1.8	− 1.0	− 0.8	− 0.4	+ 0.9	+ 1.1	+ 1.3	+ 1.2	+ 1.6	+ 1.5	+ 0.8

it was found near the end of the month that since the previous month the electrometer had been disturbed and was so out of adjustment that at the time of great deflection the needle would touch one of the quadrants and charge it from the battery. As it was not known when this disturbance happened, the records of the whole month were discarded, and were not measured.

With the exception of the April records, all measurable records for the sixteen months—273 days in all—have been included in making up the averages, and there have been no interpolations. The records have all been measured by me, personally, as have all the other records referred to in this volume. While it may be an open question whether the records of greatly disturbed days should be included in determining the mean diurnal potential gradient, it is important that there should be no suspicion of intentional selection of favorable days in making a comparison of two phenomena which are suspected of being related.

A careful inspection of Table II will show that in it, as in Table I, there are indications of two different types of diurnal variation, though the two are not so sharply defined as in the case of the earth potential variations. In order that these two types may be compared with the earth potential curves, they are plotted in the same way. Thus, in Figure 4 Curve

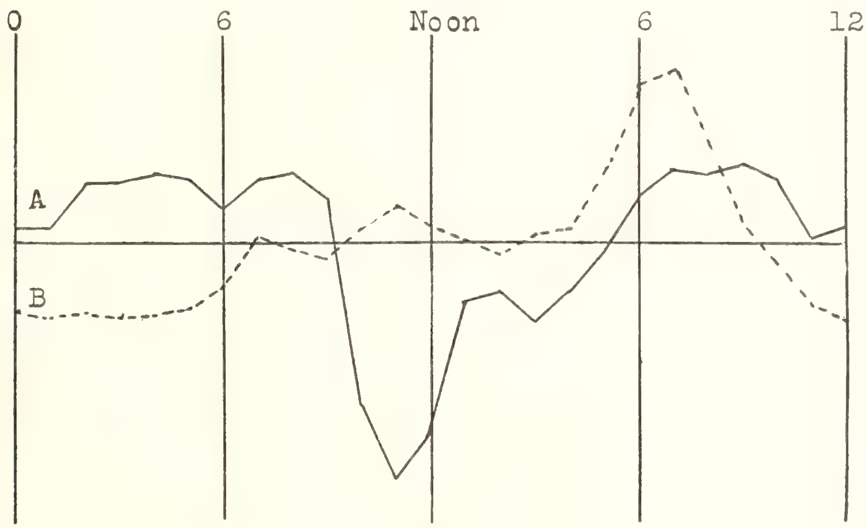

FIGURE 4.

Curve A indicates mean diurnal variation of air potential gradient for eleven months between September, 1923, and December, 1924.

Curve B indicates mean diurnal variation for the months June–September, 1924.

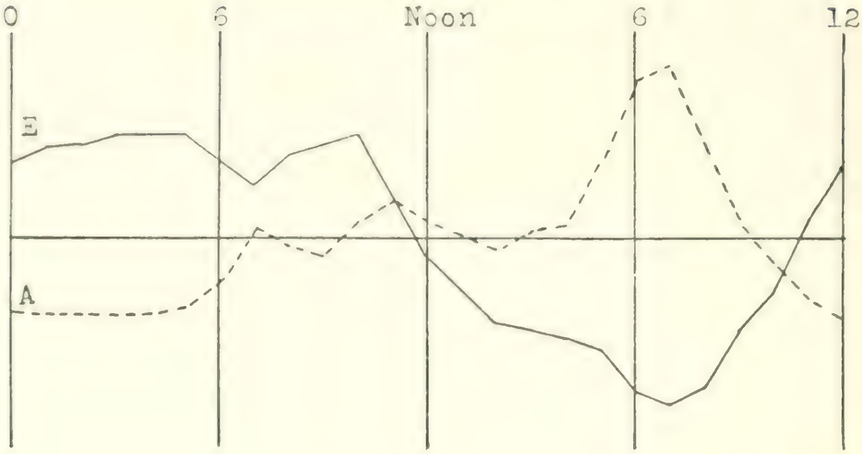

FIGURE 5.

Comparison of diurnal variation of earth potential with diurnal variation of air potential gradient for the same period.

Curve E is a reproduction of Curve B in Figure 3, and Curve A is a reproduction of Curve B in Figure 4.

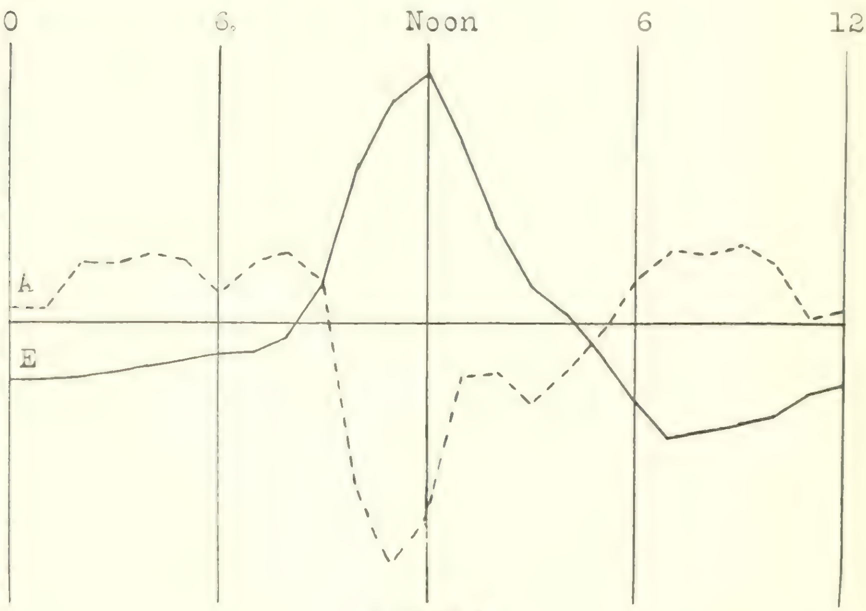

FIGURE 6.

Comparison of mean diurnal variation of earth potential and air potential gradient variation for eleven months between September, 1923, and December, 1924.

Curve E indicates the earth potential variation and Curve A the air potential gradient variation.

A gives the mean diurnal variation for eleven of the fifteen months, and Curve B shows the variation for the months June, July, August, and September, 1924. The two curves are seen to be closely related to the earth potential curves for the corresponding periods except that the signs of their deflections are inverted, that is, when the positive charge of the earth increases the atmospheric potential gradient decreases, and *vice versa.* This is more plainly shown in Figures 5 and 6, where each set of corresponding curves is compared directly. In these figures E represents the earth potential curve and A the air potential curve.

This relationship between the diurnal variation in earth potential and in atmospheric potential gradient may be still more plainly shown by further comparisons. Referring again to Table II, it may be seen that the months, November and December, 1923, and January, 1924, show a markedly different diurnal variation from the other months of the table. The diurnal variation for these months is distinguished by unusually high negative values in midday, thus giving a very pronounced minimum, such as is apparently characteristic of the winter type.

The mean values given in this table are based upon the records of 19 days in November, 15 days in December, and 15 days in January. During

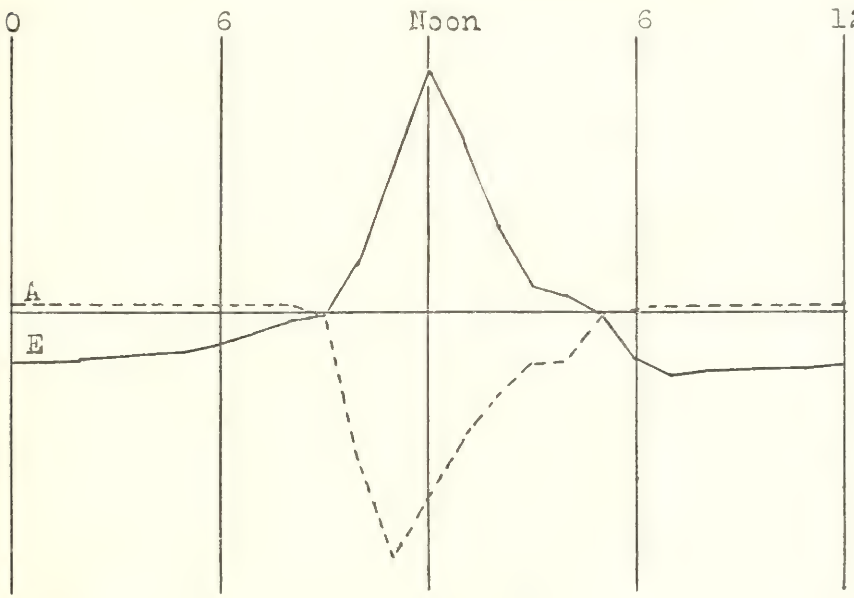

FIGURE 7.

Curve E indicates the earth potential variation and Curve A the air potential gradient variation for the months November, December, 1923, and January, 1924.

the same period 88 daily records of earth potential variation were secured In Figure 7 the mean diurnal variations of the two phenomena for this whole period, instead of the averages of the monthly means, are compared.

The two curves in Figure 7 show conclusively that for the period under consideration the atmospheric potential gradient increased when the negative potential of the earth increased and decreased when the positive potential of the earth increased.

It should be borne in mind that the two sets of records here compared are, as far as possible, independent of each other. The two electrometers whose deflections were recorded stood on separate piers, were surrounded by separate cages, were charged from separate batteries and their deflections were recorded on separate drums.

In one instance the electrometer case was connected to earth, the two pairs of quadrants were connected to separate wires which extended upward into the free air, and the needle was charged by a battery, one terminal of which was connected to earth through the city water system. The other electrometer stood on a different pier which was enclosed in a separate wire cage. The needle was charged from a battery, one terminal of which was earthed to the city water system. One pair of quadrants was connected to the metal case of the instrument, to the large cage, and to the earth. The other pair of quadrants was connected to an insulated conductor which was suspended inside the wire cage. The two instruments were effectually shielded from each other's induction, and the only way an electric charge could pass from one to the other was through the earth and through the battery by which the needle of the air potential electrometer was charged.

Since both of the phenomena under consideration are of an electrostatic nature, the only possible action of the one upon the other would have to be of the nature of electrostatic induction, and this possibility seems to have been excluded. Later when the two instruments were standing on the same pier, in the same cage, and their needles were charged from the same battery terminal, the relation between their deflections was as before.

The air potential electrometer was moved into the cage with the earth potential electrometer on February 12th. During the month of March earth potential records were secured for 26 days and air potential records for 24 days. In order that a comparison of the daily range of variation of the two phenomena may be seen these records are given in Tables III and IV, and the two monthly mean values are compared in Figure 8. It may be seen from this figure that the variation in both phenomena during the month of March was intermediate between the extreme summer and winter types, the maxima and minima in both cases occurring at 10 a.m. and 8 p.m.

Table III.

Diurnal Variation of Earth Potential for the Month of March, 1924.

Date	1	2	3	4	5	6	7	8	9	10	11	Noon
2	−1	0	+1	+1	+2	+2	+1	+2	+2	+6	+5	+3
4	0	+1	+2	+3	+4	+4	+5	+5	+5	+7	+7	+8
5	−1	0	+1	+3	+4	+5	+6	+6	+6	+18	+19	+10
6	−2	0	0	+1	+1	+1	+2	+2	+3	+21	+22	+13
7	−1	0	+1	+2	+3	+5	+5	+6	+7	+19	+16	+7
8	−2	−2	−2	−3	−3	−3	−3	−2	+3	+11	+5	+6
9	−6	−7	−7	−6	−6	−5	−6	−5	+1	+14	+14	+12
10	−3	−2	−4	−3	−2	−2	−2	0	+3	+8	+8	+7
12	−2	−1	−2	−2	−2	−1	−2	+3	+4	+5	+3	+4
13	−2	−2	−2	−2	−1	−2	−2	+1	+6	+7	+6	+7
14	−5	−4	−4	−4	−4	−4	−4	−1	+3	+11	+10	+10
15	−4	−4	−3	−3	−2	−2	−2	−1	+3	+9	+10	+10
16	+1	0	+1	+1	+2	+2	+2	+7	+11	+13	+13	+12
17	−2	−3	−2	−2	−2	−2	−1	−1	+1	+12	+11	+11
18	−2	−2	−2	−3	−3	−3	−3	+1	+4	+1	+2	+7
19	−3	−3	−3	−3	−3	−3	−2	+2	+8	+9	+10	+9
20	−3	−3	−3	−3	−2	−2	−3	0	+3	+11	+12	+12
21	−3	−3	−3	−3	−3	−3	−3	+1	+8	+5	+6	+9
22	−3	−3	−3	−3	−3	−3	−2	0	+3	+12	+12	+10
23	−2	−2	−2	−3	−3	−2	−2	0	+4	+4	+3	+4
24	−3	−3	−3	−2	−2	−2	−1	+1	+2	+2	+2	+2
25	−2	−2	−2	−1	−2	−2	−2	−1	+2	+4	+9	+11
28	−2	−2	−1	−1	−2	−2	−2	−1	−1	+8	+8	+7
29	−2	−2	−2	−2	−3	−3	−3	+2	+8	+4	+7	+7
30	−3	−3	−3	−4	−4	−5	−5	+1	+7	+10	+4	+8
31	−3	−3	−3	−3	−3	−3	−3	0	+5	+15	+12	+10

Date	1	2	3	4	5	6	7	8	9	10	11	12
2	+2	0	−1	−4	−4	−4	−4	−4	−4	−3	−2	−1
4	+6	+1	−4	−5	−6	−7	−8	−5	−4	−4	−2	−1
5	+2	+5	−7	−8	−8	−8	−9	−9	−6	−6	−4	−3
6	+2	−3	−5	−6	−6	−6	−7	−8	−7	−5	−4	−3
7	−1	−4	−5	−5	−6	−7	−8	−7	−6	−3	−3	−2
8	+4	+4	+2	+3	+3	+1	−1	−3	−3	−4	−3	−2
9	+10	+9	+7	+7	+6	+2	−2	−4	−6	−6	−5	−5
10	+6	+3	+1	+3	+2	0	−3	−6	−6	−5	−4	−3
12	+6	+5	+3	+3	+1	−2	−5	−6	−6	−5	−4	−3
13	+5	+5	+4	+4	+4	+1	−4	−5	−6	−5	−4	−2
14	+8	+6	+6	+5	+4	0	−3	−7	−8	−7	−7	−6
15	+10	+8	+7	+4	+2	−1	−4	−6	−7	−7	−6	−6
16	+10	+6	+1	−4	−8	−12	−14	−16	−8	−4	−3	−1
17	+7	+6	+3	0	−2	−6	−8	−9	−9	−6	−5	−3
18	+8	+5	+3	+3	0	−2	−3	−5	−4	−3	−2	−2
19	+8	+7	+4	+2	0	−3	−7	−8	−7	−7	−5	−4
20	+11	+7	+5	+2	−2	−7	−9	−9	−8	−6	−5	−4
21	+7	+5	+3	+1	−3	−5	−5	−5	−4	−3	−3	−3
22	+8	+6	+4	+1	−2	−7	−7	−7	−7	−5	−3	−3
23	+2	+1	+1	0	−1	−1	−1	−2	−1	−2	−2	−1
24	+1	+2	+2	+1	+1	+1	0	+1	0	0	−1	−2
25	+9	+6	+4	+2	−1	−4	−5	−6	−5	−4	−3	−2
28	+5	+4	+2	−1	−2	−3	−3	−3	−4	−4	−2	−2
29	+5	+5	+4	+3	+1	−1	−3	−3	−4	−4	−3	−2
30	+7	+5	+2	+1	−2	−5	−6	−6	−5	−4	−3	−3
31	+4	+6	+3	+1	−1	−4	−7	−8	−8	−6	−5	−3

TABLE IV.

Diurnal Variation of Air Potential Gradient, March, 1924.

Date	1	2	3	4	5	6	7	8	9	10	11	Noon
2	−8	−10	−18	−19	−16	−15	−15	−15	+6	+5	+4	+6
5	+3	+1	+3	+3	+3	+11	+11	+3	+4	−11	−14	−15
6	+26	+30	+8	+13	+14	+16	+16	+23	+1	−26	−32	−26
7	+2	0	−2	−4	−7	−7	−9	−11	−13	+2	+2	+3
8	+3	+2	+2	+1	−1	−2	−1	−4	−3	−20	−18	−8
9	0	0	−2	−3	−3	−4	−4	−3	−3	−18	−14	−2
10	−3	−4	−3	−6	−8	−9	−9	−1	−4	−5	−3	0
12	+2	+1	−1	0	0	+1	+1	−3	−5	−5	−4	−4
13	+1	−4	0	−2	−1	−3	−1	−1	−6	−4	−4	−4
14	+1	−1	−3	−3	−3	−4	−2	0	−3	−5	−5	−3
15	−1	−2	−3	−3	−3	−4	−5	−3	−3	−9	−6	−3
16	+1	+1	+2	+3	+3	+2	+2	−1	−7	−10	−9	−7
17	+1	+1	0	0	−5	−2	−3	−4	−1	−10	−4	−2
18	+3	+5	+6	+5	+6	+6	+6	+1	−3	−7	−5	−8
19	+4	+4	−1	−5	−6	−6	−1	−2	6	−7	−6	−4
20	−2	−1	0	−1	−2	−2	−2	−2	−1	−6	−5	−5
21	+1	0	0	0	0	−1	−1	−1	−4	−1	−1	−2
22	0	0	0	−1	−1	−1	−1	0	−1	−6	−4	−1
23	−1	−1	−1	−2	−2	−2	−3	−2	−2	0	+1	−1
24	0	−1	−1	−1	0	0	−1	−2	−3	−5	−2	+1
25	+1	−1	0	−1	0	0	0	+1	1	7	−8	−7
28	+1	0	−1	0	+1	+1	+1	0	+1	−16	−12	−6
29	0	0	0	0	0	0	+1	−6	−9	−4	−1	+2
31	+2	+1	+1	+1	0	−1	−1	0	−2	−14	−10	−5

Date	1	2	3	4	5	6	7	8	9	10	11	12
2	+12	+14	+12	+14	+13	+11	+10	+9	+5	+12	−13	−3
5	+10	−6	−3	−1	−1	+1	+5	+7	+4	+7	+1	+2
6	−20	−15	−11	−10	−7	−2	+2	+2	0	−1	−1	+10
7	+3	+1	+1	+1	+1	−3	+1	+3	+7	+5	+5	+4
8	−5	+3	+5	+4	+4	+5	+6	+6	+6	+5	+4	+2
9	+4	+5	+5	+5	+5	+7	+8	+6	+4	+2	+1	0
10	+3	+6	+3	+3	+3	+5	+5	+5	+3	+4	0	−2
12	−3	0	0	−1	−1	0	+2	+3	+3	+3	+3	+2
13	+1	+2	+2	+2	+2	+2	+3	+5	+5	+3	+3	+2
14	0	+2	+3	+3	+3	+4	+2	+4	+2	+1	0	0
15	0	+2	+3	+4	+4	+5	+6	+4	+3	+3	+1	+1
16	−4	−3	−2	−2	−1	+2	+1	+3	+4	+4	+4	+3
17	−1	+2	+3	+3	+4	+3	+4	+3	+2	+2	+2	+2
18	−8	−7	−4	−1	+1	+2	+3	+2	+3	+2	+1	+1
19	−2	−2	−1	0	0	+2	+2	+4	+6	+5	+5	+6
20	−3	+7	+3	+3	+4	+4	+4	+1	0	−1	−1	0
21	+1	−2	+3	+3	+3	+3	+1	0	0	0	0	+1
22	+1	+2	+2	+3	+4	+3	+4	+5	+3	+1	0	0
23	0	0	−1	−1	+1	+1	+1	+2	+1	+1	+1	+1
24	+1	+1	+2	+3	+2	+2	+1	0	+1	+1	0	0
25	−4	+4	−3	−1	+1	+5	+5	+6	+4	+2	+2	+1
28	+1	0	+1	+3	+4	+3	+3	+1	+2	+1	0	+1
29	+4	+3	+3	−1	+1	+2	+3	+3	+3	+2	+2	+1
31	−1	+1	+2	+3	+4	+4	+5	+6	+5	+3	+3	+2

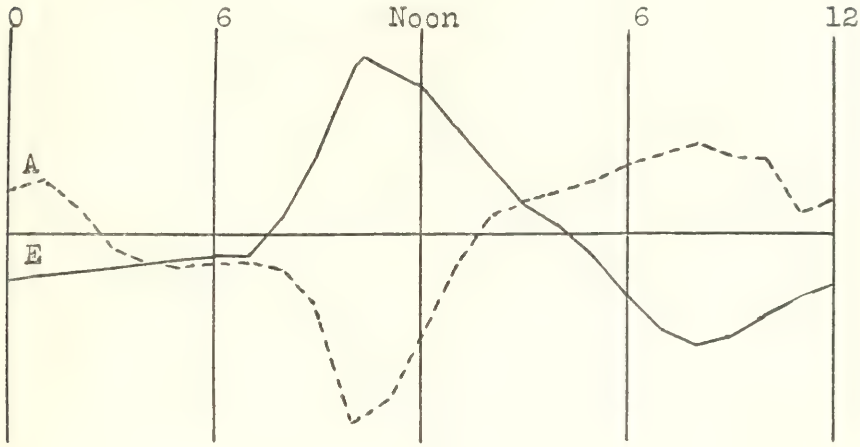

FIGURE 8.

Curve E indicates the earth potential variation and Curve A the air potential gradient variation for the month of March, 1924.

It may also be observed by referring to Table III that the earth potential variations were unusually large and of a different character for the days March 2–7. This was probably due to the passage of a large sun spot group across the face of the sun. Such a group was reported from the Mount Wilson Observatory as just coming into view on February 24th. On February 28th, at 3:30 p. m., a sudden great disturbance was recorded by both the earth potential and air potential electrometers, and the records did not return to their normal range until about March 6th or 7th.

By plotting the curves showing the mean diurnal variation of the two phenomena for March 2nd, 5th, 6th, and 7th, the days for which simultaneous records are at hand, it will be seen that even under these disturbed conditions the two curves preserve their general relation to each other.

Theory of Atmospheric Potential Gradient

From the time of Franklin's identification of lightning as an electric discharge down to the beginning of the 19th century, it seems to have been universally believed that the atmosphere contained at all times considerable free charges of electricity which were usually of the positive sign. In 1803, Paul Erman* of Berlin showed that either positive or negative charges could apparently be drawn at will from the air, and that all the phenomena of atmospheric electricity which are usually observable in fine weather may be explained satisfactorily as induction phenomena due to a negatively charged earth.

* Gilbert's *Annalen,* XV, 386 (1803).

This important discovery of Erman's seems to have been received with incredulity, though the following year Biot and Arago found that with a collecting wire suspended *below* a balloon they could observe only negative charges at its upper end. Accordingly, Erman's fundamental paper is seldom referred to in the literature of Atmospheric Electricity, and is not even mentioned in Mottelay's "Biographical History of Electricity and Magnetism," though frequent mention is made of less important work by Erman.

In 1836, the same explanation of atmospheric potential gradient was made by Peltier,* who devised an apparatus for measuring the potential gradient which was based upon the theory that it was merely a manifestation of the electrical field of the earth.

Sir William Thomson (Lord Kelvin) also devised a collecting apparatus based upon the same theory. In his presidential address before the Society of Telegraph Engineers,† in 1874, Thomson said:

> I do not say too much, then, when I say that the statement that the air is positively electrified has been at all events a subject for ambiguous and contradictory propositions; in fact, what we know by direct observation is, that the surface of the earth is negatively electrified, and positive electrification of the air is merely inferential.

Again, he says:

> The result that we obtain every day of fair weather in ordinary observations on atmospheric electricity is precisely the same as if the earth were negatively electrified and the air had no electricity whatever.

Franz Exner of Vienna, has given much attention to the distribution of the earth's negative charge over its surface, as indicated by its potential gradient, and has reached the conclusion that this distribution is such as an electrostatic charge would have on an uneven surface such as that of the earth; i. e., the electrical density is greater the greater the curvature of the surface over a given region. He has also given an estimate of the negative potential of the earth, which would account for the potential gradient over its surface as 4×10^9 volts.‡ In this connection he says:

> 1. Of all theories of atmospheric electricity up to the present time, only that of Peltier does not contradict known facts.
> 2. Peltier's theory explains all known phenomena completely.

The present investigation seems to show that though the atmospheric potential gradient is much more subject to local disturbances than is the earth potential, in their general features the two phenomena vary simultaneously and in opposite directions, as they should from the theory of

* *Ann. d. Chim. et d. Phys.*, LXII. (1836.)
† *Soc. Tel. Eng. Jour.*, Vol. III, p. 12. (1874.)
‡ *Repertorium der Physik*, Vol. 22, p. 479 (1886).

Erman and Peltier. In fact, had the variation of the potential of the earth been first discovered, the variation of the atmospheric potential gradient would certainly have been predicted from it.

Seasonal Variation of Atmospheric Potential Gradient

The data on atmospheric potential gradient so far given have dealt only with the diurnal variation of the same. That there is also a seasonal variation of this gradient has long been known; but the data which have been recorded at this station are not adapted for computing that variation. Thus, the actual potential gradient in volts per meter at Palo Alto is not known. The electrometer which has been used in recording the daily variation has not always stood in the same position, nor has its needle always been charged from the same battery. The measurements which have been made in different months are, for these reasons, not quantitatively comparable. All that has been attempted has been a qualitative comparison of the simultaneous variations of the earth potential and the atmospheric potential gradient. The results of this comparison seem to indicate that Erman's theory of the inductive nature of the atmospheric potential gradient is the true explanation of this phenomenon, and that the diurnal variation of this potential gradient is due to the inductive action of the sun's negative charge.

The question whether the seasonal variation of the earth's atmospheric potential gradient may also be explained by the sun's induction is an important one, and it seems desirable to consider it briefly in this place.

It is generally known that at all stations where the altitude of the sun varies considerably during the year the atmospheric potential gradient is greater in winter than in summer—the data from Helwan, in Egypt, furnishing the only known exception.

On page 14, Volume I, of this bulletin attention was called to the fact that if there is a shifting of the negative charge of the earth due to the induction of a negative charge upon the sun, the winter hemisphere of the earth should be, on the whole, electronegative to the summer hemisphere, while the accompanying curves showing the diurnal variation of the earth potential at Palo Alto at different times of year indicate that such is the case.

In *Science* of May 25, 1923, was published a paper entitled, *On an apparent effect of the sun's electrical charge on the yearly variation of atmospheric potential gradient.* In this paper it was argued that a displacement of the earth's negative charge toward the north or south should be proportional to that component of the sun's repulsive force which acts in the direction of the given displacement, and that this N-S component of the sun's repulsion at a given place should vary approximately as the sine of the sun's angular distance from the zenith at noonday. Curves

were given showing the variation of the air potential gradient from month to month at a number of stations both north and south of the Equator, as shown by the published records of these stations, and these curves were compared with curves showing the monthly variations of the sines of the angles of the sun's zenith distance at the same stations. The relation between the two sets of curves seemed to indicate that the phenomena represented were due to a common cause; but the article was criticized by Dr. L. A. Bauer in *Science* of July 27, 1923, on the ground that the data on atmospheric potential gradients which were used in my paper were not reliable. Since the publication of Dr. Bauer's paper I have found in Mache and von Schweidler's *Die Atmosphärische Elektricität,* page 25, a curve which is there said to represent the mean monthly values of atmospheric potential gradient for all the stations in Europe which are provided with self-recording instruments. This curve is reproduced in Curve A, Figure 9, while Curve B in the same figure shows the sines of the angles of the sun's zenith distance on the first day of each month for latitude 45 degrees north. The agreement between the two curves is surely as close as could be expected if our hypothesis is correct.

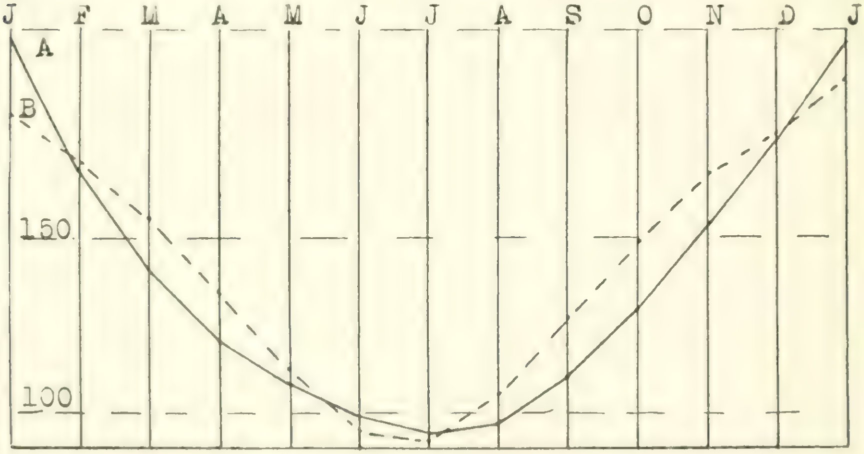

FIGURE 9.

Comparison of mean monthly variation of air potential gradient for all European stations having self-recording instruments with the sines of the angles of the sun's zenith distances on the first days of the respective months at latitude 45 N.

Curve A indicates the monthly values of potential gradient and Curve B the sines of the sun's zenith distances.

There has also recently come to hand reliable data from the southern hemisphere. In the September, 1924, number of *Terrestrial Magnetism*

and Atmospheric Electricity Mr. Andrew Thomson has published a *Preliminary Report on the Atmospheric Potential-Gradient Recorded at the Apia Observatory, Western Samoa, May, 1922, to April, 1924.* On pages 99 and 100 of his article Mr. Thomson has given mean monthly values of the potential gradient for the year May, 1923–April, 1924. He calls attention to the small number of days used in determining this mean potential gradient, and says, "It is doubtful if the available data are yet sufficient to draw any very definite conclusion regarding the precise character of the annual variation of potential gradient at Apia." Nevertheless, it may be worth while to compare his results with those which would be given by our theory of the relation of the annual variation of potential gradient to the sun's induction. This is done in Figure 10, where the continuous line represents Mr. Thomson's data and the dashed line gives the sines of the angles of the sun's zenith distance at Apia on the first day of each month at noon. The only month for which a serious discrepancy appears between the two curves is February, for which month Mr. Thomson's data include records of only seven days.

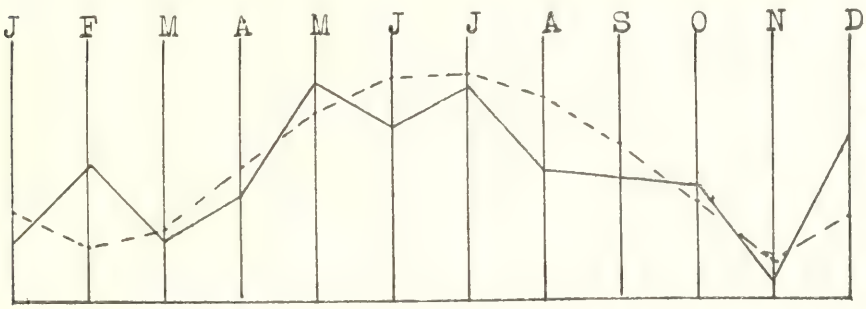

FIGURE 10.

Comparison of mean monthly values of atmospheric potential gradient at Apia, Samoa, for the year May, 1923–April, 1924, with the sines of the angles of the sun's zenith distances at Apia on the first days of the respective months.

The continuous line represents the monthly values of the potential gradient and the dashed line the sines of the angles of the respective zenith distances of the sun.

In the light of what has preceded, it seems to the writer that the conclusion is justified that the cause of the increase of potential gradient in the winter time is the excess of the negative charge of the earth on its winter hemisphere, due to the inductive repulsion of the negative charge of the sun.

One Cause of Electric Potential Differences Between Clouds

Any cloud which is unelectrified with reference to its surrounding air should show positive charges on its lower surface and negative charges on

its upper surface, due to the induction of the earth's electric field. This condition was observed by Wigand* in his balloon ascensions for studying the electrical condition of the air. No other free charges were found, though his investigations extended to an altitude of nearly nine kilometers (over five miles).

Any cloud from which precipitation has taken place has necessarily become charged to the potential of its surroundings. If it rises, as it may do with the elevation of the dew point level, it is negatively charged with reference to the earth's field at its level. If such a cloud sinks, due to the cooling of the air below it, it will become positively charged with reference to the atmosphere at its level. Hence two clouds whose potentials have been adjusted to different levels may be at different potentials when brought to the same level. The same may be true of two clouds formed at the same elevation, but in regions of different potential gradient, as over mountains and over plains or valleys.

Air-Earth Currents

The fact that there is always a potential gradient in the air together with the fact that while the air is a very good insulator it always contains some free ions, both + and —, seems necessarily to lead to the conclusion that there must be an electric current flowing from the air downward into the earth. In recent times there has been considerable attention given to this hypothetical current, whose magnitude has been computed by multiplying the observed potential gradient of the air by its measured conductivity. The current calculated in this way is always much too feeble to admit of direct measurement, amounting, on the average, to about 1/100,000 ampere to the square mile; but taken over the whole surface of the earth it amounts to about 2,000 amperes, and would be sufficient to increase the positive potential of the earth at a rate of more than three million volts in one second. Since there are no known reasons for assuming a return current flowing from the earth into the air, physicists who believe in the air-earth current have found the persistence of the negative condition of the earth's surface inexplicable.

The explanation of potential gradient proposed by Erman and Peltier would make the hypothesis of a continuous air-earth current unnecessary, and would give a different interpretation to the quantity obtained by multiplying the potential gradient by the atmospheric conductivity. Thus, if the air were a good conductor there could be no potential gradient in it. If it were a perfect insulator the potential gradient would be at its maximum value. Wherever the conductivity of the air increases the potential gradient must decrease. This relation explains the observation so frequently made

* *Ann. d. Phys.*, Vol. 66, p. 81 (1921).

that the number of free ions in the air seems to vary inversely as the potential gradient. If the one does vary inversely as the other, then their product should give the potential gradient which the earth would have if surrounded by a medium of invariable conductivity which might be taken as unity. This, I have called "the corrected potential gradient of the air." *It is this corrected potential gradient which should vary with the variation of the earth's electric charge.* All observed variations of potential gradient are subject to disturbances due to changes in atmospheric conductivity.

In the series of balloon ascensions already referred to, Wigand* found that up to a height of about nine kilometers the product of the potential gradient into the conductivity of the air remained constant at a given altitude, but that it fell off with the altitude at the rate of about two per cent per kilometer.

If the potential gradient were due to an electric field between an upper, charged layer in the air and the surface of the earth, it should not decrease with an increase of altitude. In order for this to occur there would have to be an excess of positive ions in the lower atmosphere, and Wigand, like all his predecessors, found no excess of such positive ions. On the contrary, he found an apparent slight excess of negative ions everywhere above an altitude of 500 meters.

The Moon's Influence Upon Magnetic and Electric Phenomena Upon the Earth

On pages 18–20 and 23–25 of Volume I, attention was called to the influence of the moon upon the diurnal variation of earth potential and of earth-currents, and it was mentioned that on page 892 of *Kosmische Physik* Arrhenius says that there is an appreciable decrease in the atmospheric potential gradient a short time before the upper culmination of the moon. As the previous measurements of atmospheric potential gradient have usually been made between the earth and a point in the atmosphere, it was thought advisable to verify this observation between two points in the air. This was done for the 73 days for which air potential records are available during the months October, 1923–January, 1924, viz., 26 days in October, 18 in November, 14 in December, and 15 in January.

In making this determination Chapman's method† of subtracting the mean potential gradient at a given hour of the day for the whole month from each of the daily measurements of potential gradient at that hour, and distributing the residuals with their appropriate signs to the proper hour of the lunar day was used. The algebraic sums of these residuals divided by 73 then gives the mean lunar variations of potential gradient for the respective

* *Ann. d. Phys.*, LXVI, 81 (1921).

† *Phil. Trans.*, 214, 295–317 (1914).

hours. The results in terms of millimeters on my record sheets are given in Table V.

TABLE V.

Lunar Diurnal Variation of Air Potential Gradient for 73 Days.

Hour	1	2	3	4	5	6	7	8	9	10	11	U.C.
Oct.	+ 8	+ 49	+ 36	+ 49	+ 118	+ 103	+ 113	+ 131	+ 98	+ 35	+ 72	− 31
Nov.	− 22	− 106	− 158	− 137	− 31	+ 1	+ 74	+ 55	+ 149	+ 148	+ 137	+ 52
Dec.	+ 51	+ 119	+ 70	+ 128	+ 120	+ 138	+ 152	+ 87	+ 37	+ 23	− 24	− 84
Jan.	+ 21	+ 3	− 31	− 35	− 60	− 114	− 121	− 135	− 114	− 80	− 74	+ 5
Sum	+ 58	+ 65	− 83	+ 5	+ 147	+ 128	+ 218	+ 138	+ 170	+ 26	+ 111	− 58
Hourly Mean	+ 0.8	+ 0.9	− 1.1	0.0	+ 2.0	+ 1.8	+ 3.0	+ 1.9	+ 2.3	+ 0.4	+ 1.5	− 0.8
Hour	**13**	**14**	**15**	**16**	**17**	**18**	**19**	**20**	**21**	**22**	**23**	**24**
Oct.	− 72	− 139	− 76	− 62	− 86	− 85	− 114	− 83	− 20	− 38	− 46	− 27
Nov.	− 33	− 17	+ 9	− 29	− 14	+ 29	+ 13	+ 18	+ 33	+ 47	+ 48	+ 18
Dec.	− 98	− 88	− 111	− 161	− 64	− 135	− 86	− 90	+ 5	+ 1	− 13	+ 8
Jan.	− 49	+ 1	− 23	+ 18	+ 80	+ 52	+ 99	+ 128	+ 128	+ 114	+ 81	+ 47
Sum	− 252	− 243	− 201	− 234	− 84	− 139	− 88	− 27	+ 146	+ 124	+ 70	+ 46
Hourly Mean	− 3.4	− 3.3	− 2.8	− 3.2	− 1.2	− 1.9	− 1.2	− 0.4	+ 2.0	+ 1.7	+ 1.0	+ 0.6

As may be seen, Table V contains very great irregularities, which are to be expected when it is remembered that it includes not only the lunar variations but all the irregularities in the solar variations for the periods covered. It is too much to expect that these will cancel each other in only 73 days. Nevertheless, the indication of a lunar variation of potential gradient is very plain.

To test this question still further, the determination of the moon's influence upon the potential gradient was made in another manner. The number of days for which the residuals used in Table V had positive signs and the number for which the signs were negative at a given lunar hour were determined. The result is given in Table VI. Thus it will be seen that at the time of the moon's upper culmination there were eight more days having positive residuals than there were having negative residuals, while for the hour preceding upper culmination there were seventeen more positive than negative residuals.

TABLE VI.

Number of Days for which the Potential Gradient Variation was Greater and Number for which it was Less than the Mean at the Given Lunar Hours.

Hour	1	2	3	4	5	6	7	8	9	10	11	U.C.
Days.........	+ 32	+ 35	+ 33	+ 37	+ 42	+ 35	+ 41	+ 38	+ 43	+ 43	+ 43	+ 39
Days.........	− 41	− 33	− 36	− 35	− 29	− 33	− 31	− 33	− 28	− 29	− 26	− 31
Dif............	− 9	+ 2	− 3	+ 2	+ 13	+ 2	+ 10	+ 5	+ 15	+ 14	+ 17	+ 8
Hour	13	14	15	16	17	18	19	20	21	22	23	24
Days.........	+ 28	+ 25	+ 24	+ 20	+ 28	+ 27	+ 25	+ 29	+ 32	+ 35	+ 32	+ 38
Days.........	− 42	− 45	− 46	− 51	− 40	− 43	− 45	− 43	− 37	− 34	− 37	− 33
Dif............	− 14	− 20	− 22	− 31	− 12	− 16	− 20	− 14	− 5	+ 1	− 5	+ 5

The data of tables V and VI are shown graphically in Figure 11, where the results of Table V are shown by the continuous curve and those of Table VI by the dashed curve. The agreement in general form of the two curves is so close as to make the actual existence of the phenomenon under consideration a practical certainty.

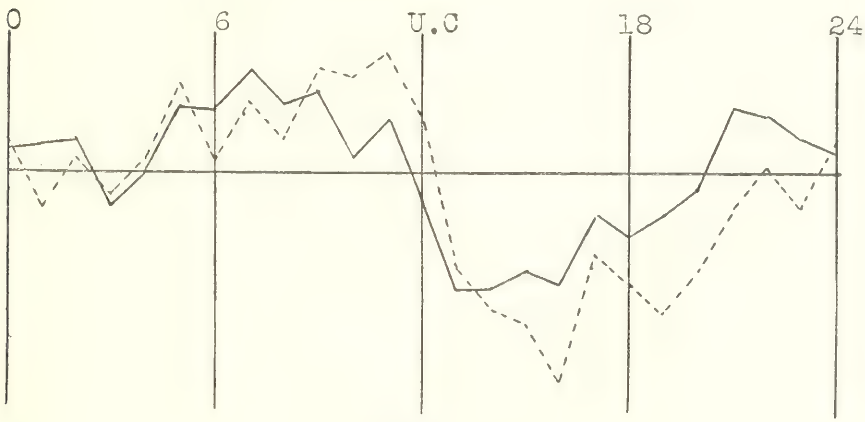

FIGURE 11.

Lunar diurnal variation of atmospheric potential gradient.

The continuous curve represents the mean lunar diurnal variation of atmospheric potential gradient for 73 days. The dashed curve represents the excess of positive or negative variations of potential gradient at the given lunar hour for the same period.

Figure 12 shows the solar and lunar diurnal variations for the same period and drawn to the same scale. S represents the solar and L the lunar

curve. This seems to indicate that the lunar diurnal variation is approximately one-seventh as great as the solar variation.

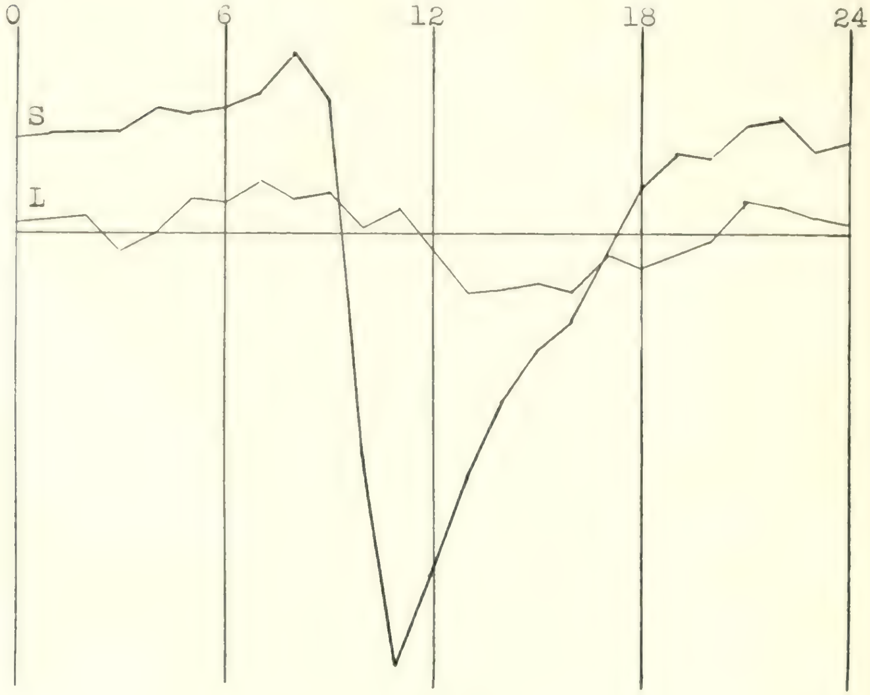

FIGURE 12.

Comparison of solar and lunar diurnal variation of air potential gradient for the period Ocotber, 1923–January, 1924.

Curve S represents the solar and Curve L the lunar diurnal variations on the same scale.

It will also be seen that the two curves are not of the same shape, the potential gradient minimum due to the moon's influence coming from one to four hours after the moon has passed the meridian. In Figure 5 of Volume I is given a curve showing the lunar diurnal variation of earth potential which is more nearly of the form of the solar curve than are the curves here given in Figure 11. The relative magnitudes of the solar and lunar effects seem to be approximately the same in the two cases, the lunar variations of earth potential running from one-seventh to one-tenth the magnitude of the solar variations.

In Figure 13 the curve for lunar diurnal variation of potential gradient is shown with Figure 7 of Volume I, which shows the lunar diurnal variation of the N-S earth-current at Ebro Observatory for nine

synodic periods. The earth-current variation is shown by the broken line. The agreement in shape of the two curves is such as to strongly suggest their dependence upon a single cause.

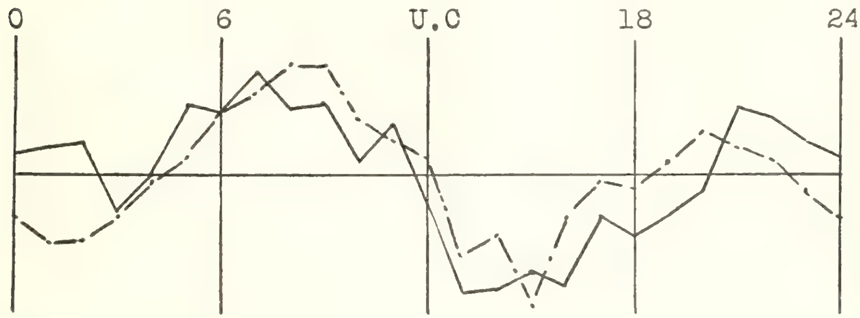

FIGURE 13.

Lunar diurnal variation of air potential gradient at Palo Alto compared with lunar diurnal variation of N–S earth-current at Ebro Observatory.

The continuous line represents the air potential variation and the broken line the earth-current variation.

That the lunar influence upon electric phenomena is similar in character to its influence upon magnetic phenomena may be seen from Figure 14, where Chapman's data for the lunar diurnal variation of horizontal

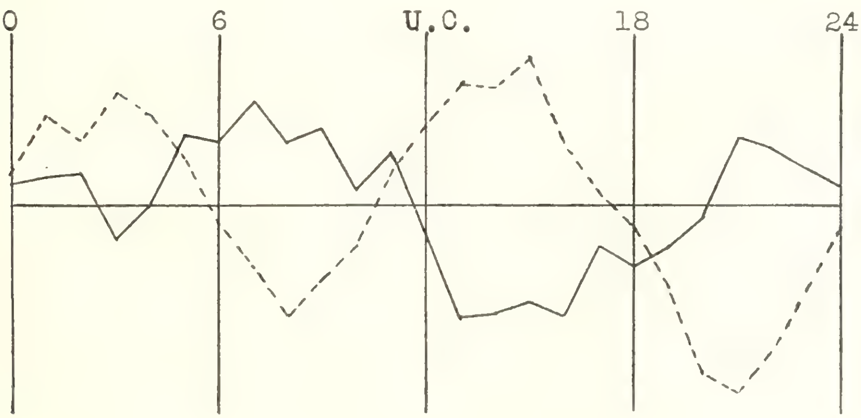

FIGURE 14.

Lunar diurnal variation of air potential gradient at Palo Alto compared with lunar diurnal variation of horizontal magnetic intensity at Pola, Austria.

The continuous line represents the potential gradient and the dashed line the horizontal magnetic intensity.

magnetic intensity for the equinoctial period is compared with our curve for lunar diurnal variation of atmospheric potential gradient. The dashed line gives the lunar diurnal variation of horizontal magnetic intensity.

The above data on the moon's influence upon terrestrial electric and magnetic phenomena show that the moon affects these phenomena in the same manner as does the sun. Whatever may be the nature of the influence of the sun upon the earth's electric and magnetic condition, the moon must exert an influence of the same character. That this influence is not gravitational is shown by the fact that the sun's electrical tides are some seven times as high as the moon's, while the moon's gravitational tides are more than three times as high as the sun's. This should dispose of Schuster's theory that the earth's magnetic elements are disturbed by tidal waves in the upper atmosphere which are supposed to carry an excess of one kind of ions.

If, as is frequently assumed, the sun is sending off streams of electrons or positive ions to the earth, there must be a similar radiation of ions from the moon to the earth, and these must be expelled from both the light and the dark sides of the moon, since a careful comparison of the moon's influence upon the air potential gradient at full moon with its influence at new moon shows no appreciable difference. If the observed effects are due to light radiation, the solar effect should be relatively many times as great as it is, and the difference between the light and dark sides of the moon would be very great. In fact, all known agencies except the inductive effects of electrical charges seem to be excluded when it is shown that the sun and moon affect *in the same manner* the electric and magnetic conditions on the earth.

Earth-Currents

The earth-current records for the period covered by this report have been the least satisfactory of all the records. Through the generosity of the Pacific Telephone and Telegraph Company, I have been given the use of three ordinary telephone grounds, the wires from which the company has brought into my observatory. The location of these grounds with reference to the surrounding country may be understood by reference to the sketch in Figure 15, which has been copied to scale from the U. S. Geological Survey sheet for this region.

In this sketch A, B, and C represent the positions of the grounds, and St. the position of my observing station. The distance from A to B is 2.6 miles, and from A to C is 1.9 miles. The irregular heavy line above and to the right of A represents the border of marshy tidal flats around San Francisco Bay, which are distant 1.3 miles from A. South and southeast of A and extending far to the northwest, at a distance of from four to nine miles, is a range of the Santa Cruz Mountains, which reach a height of

2,200 feet south of A. Station C is distant about one-fourth mile from a trolley line over which cars are run every ten minutes during the day.

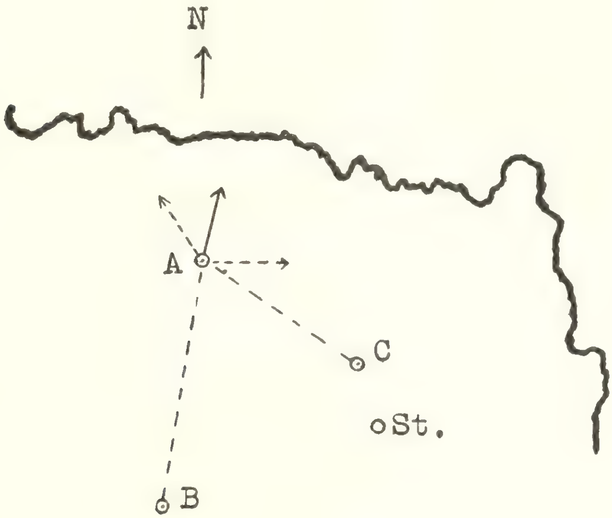

FIGURE 15.
Sketch of location of grounds for earth-current measurements.

The currents in both lines AB and AC are very irregular, so that a galvanometer placed in either of them is seldom quiet for a single second. What part of this irregular disturbance is due to trolley currents from Palo Alto and Redwood City lines it is impossible to say. The near Palo Alto lines are across San Francisquito Creek, which is here 30 or 40 feet deep, but which carries no water in the summer. The fact that the currents are least disturbed between 2 o'clock and 5 o'clock in the morning suggests the probability of artificial disturbances. On the other hand, when a similar ground was taken at my observing station, only 300 feet from a trolley line, the irregular disturbances were so great as to make the determinations of the regular variations impossible.

The method of recording the variations of the earth currents is by using a D'Arsonval galvanometer with a heavy coil carrying only a few turns of No. 20 wire, suspended in a brass beaker which is placed between the magnet poles and is filled with heavy machine oil to aid in damping out the most rapid vibrations. Since these vibrations are recorded photographically on a drum which rotates only one millimeter in three minutes, a very slow paper is used, and rapid oscillations give a blur instead of a line on the record sheet.

The earth-current records published in Volume I were between ground B and a ground about halfway between A and C. The present grounds were placed at my disposal last May, and for a time two similar galvanometers were placed in the lines AB and AC, and the deflections of both were recorded upon the same drum. This method of comparing the two currents was unsatisfactory. The two galvanometers were not equally sensitive, and as rather frequent changes in the intensity of the currents made it necessary to change the shunts which were used with the instruments, it was very difficult to keep them at the same relative sensitivity. Accordingly, one galvanometer was taken out and the other was used on alternate days in line AB and line AC. In this way records have been kept since last June. It has usually been possible to get the same number of records from each line at a given sensitivity of the galvanometer, so that the mean current intensities in the two lines are comparable.

During the months of November and December some unusually cold weather caused the viscosity of the oil used for damping the galvanometer coil to become so great that minor variations were not recorded at all. The oil was changed for some less viscous, but there was so much difference between the records on warm days and cold days that the records for these two months were not measured.

During the months June–October 49 daily records were obtained for line AB and 50 for line AC. When changing the recording sheet each day the current was broken and the zero position of the spot of light from the galvanometer mirror was made to coincide in position with that from a fixed mirror which gave the base line from which the measurements were made. The records accordingly represent the total current intensity, and not the variation from a daily mean, as do the earth potential and air potential records.

Since nothing is known of the actual earth-current intensity between the grounds of each pair, but only the current intensity in a wire which serves as a shunt to the earth-current, all that we can actually measure is the difference in electrical potential between the two grounds. This varies greatly from day to day, and often from hour to hour. As an example of its magnitude as here recorded, it was 35 millivolts per mile from C to A and 17 millivolts per mile from A to B on January 22, 1924, at 4 p. m. This would give at that time a resultant potential gradient at A of 35.5 mv./mi. in a direction six degrees south of west. Since for the whole period under consideration the potential gradient at 4 p. m. was about two-thirds of the mean for the day, it would seem that the average potential gradient on the earth at A was about 53 millivolts per mile. This potential difference was measured by using a sensitive galvanometer and balancing it against a known e.m.f.

In order to determine the relative magnitudes and directions of this potential gradient during the five months covered by this report the hourly mean galvanometer deflections in the two lines, for the whole period, were reduced to the same length of line in both cases on the assumption that the deflections were proportional to the distance between the grounds. The direction and magnitude of the mean resultant e.m.f. for each hour of the day was then computed, and is given in Table VII. In this table the upper line shows the relative magnitude in unknown units of the potential gradient at ground A, and the lower line shows the angular variation in degrees from a N-S line. Thus, at noon the potential gradient had a magnitude of 35 units per mile and a direction 86 degrees west of south.

TABLE VII.

Direction and Magnitude of Potential Gradient in Units per Mile from Station A (Fair Oaks Lane).

A. M.	1	2	3	4	5	6	7	8	9	10	11	Noon
Mag........	45.0	51.5	53.5	51.0	51.0	38.0	11.0	9.0	12.5	30.0	31.0	35.0
Direc........	33 E	35 E	34 E	34 E	32 E	34 E	23 W	45 W	84 W	81 W	83 W	86 W
P. M.	1	2	3	4	5	6	7	8	9	10	11	12
Mag........	37.5	39.0	28.5	22.0	30.5	25.5	26.5	35.5	33.5	22.0	36.5	47.0
Direc........	90 W	92 W	82 W	72 W	82 W	76 W	37 W	15 E	12 E	17 W	21 E	33 E

When these vector quantities are added and their sum divided by 24 they give a potential gradient 12 degrees west of south of 20.3 units per mile. Since the electrons flow in a direction opposite to this conventional potential gradient, their mean direction is given by the arrow from A, and the limits of their deviation to the east and west are shown by the dashed arrows.

According to the results of this investigation, the electrons near the earth's surface in this locality flow from the mountains to the bay throughout the whole 24 hours. This is what would occur if they were seeking a water route around the earth.

In concluding this report I wish to express my sense of obligation to my friend, Professor Jeremiah W. Jenks, at whose expense this work is being published.

FERNANDO SANFORD.